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DESIGNING A BINARY COUNTER

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DESIGNING A BINARY COUNTER

by

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PREFACE

As part of the curriculum of the Electronics Engineering Course at the U. S. Naval Postgraduate School the author was assigned as a junior engineer to the Engineering Products Department, RCA Victor Division, Radio Corporation of America, Camden, N. J. for a period of eleven weeks during the winter of 1949. He was specifically assigned to assist Mr. H. C. Bryson of RCA in the pre-production development of a counter under Navy Contract NObsr-39313. This project consisted primarily of investigating miniature and sub-miniature techniques in order to produce an easily portable piece of test equipment.

Prior to, and during this period, the author studied the articles listed in the Bibliography to assist him in this assignment and in the preparation of this thesis. Using this background and the circuitry already developed by Mr. W. H. Bliss of the RCA Laboratories Division, Princeton, N. J. the author attempted to design a 400,000 to 1 counter by scaling known designs to the needs of the assigned project. By trial and error techniques barely acceptable circuits were produced. It soon became apparent that it would be highly desirable to have some means of predicting the optimum circuit design. To meet this need, and at the instigation of Mr. Bryson, the author evolved the design procedures set forth in this thesis. Three different counter circuits were built using these procedures and upon testing gave highly satisfactory results.

Rather than write a lengthy summary of the past liter-

ature on counters, the author hopes that this paper will be an extension to the literature. The only claim to true originality lies in the method for determining the optimum ratio of R_2 to R_3; it was on this phase that the author spent the major portion of his research time on this project. The other procedures set forth, however, represent a compilation in one article of known facts in other fields of electronics which are adaptable to the design of electronic counters.

It is hoped that this paper will meet the need for which it was written; to this end it is additionally being offered for publication in a technical periodical. The Bibliography herein is offered for those who wish to make a more extensive study of counters, their circuitry and applications.

The author wishes to express his gratitude to RCA for the use of their facilities, to many of their personnel for providing a pleasant stay there, and especially to Mr. H. C. Bryson for his patient assistance in the formulation and preparation of this paper.

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LIST OF ILLUSTRATIONS.

TABLE OF SYMBOLS

B^+	Plate supply voltage with respect to ground.
e_b	Plate voltage with respect to ground of the conducting tube of a stage.
e'_b	Plate voltage with respect to ground of the non-conducting tube of a stage.
e_c	Grid voltage with respect to ground of the non-conducting tube; potential of point c on conducting side of stage.
e'_c	Grid voltage with respect to ground of the conducting tube.
e_{gk}	Bias voltage, grid to cathode, of the non-conducting tube.
e_k	Cathode voltage with respect to ground; the bias source.
e_o	Computed maximum voltage output of a stage.
e_{pk}	Plate to cathode voltage of the conducting tube.
e'_{pk}	Plate to cathode voltage of the non-conducting tube.
f_2	The upper half-power frequency of a stage; the frequency at which the output voltage is down 6 db.
i_b	Plate current of the conducting tube.
r_L	Equivalent series plate load resistance.
r_p	Dynamic plate resistance of the conducting tube.
T	Time interval between incoming pulses to be counted; or 1/f.

I. INTRODUCTION

It is the purpose of this article to establish Empirical Procedures for designing Eccles-Jordan Multivibrators suitable for use in electronic counters. It does not discuss in detail any applications or the circuitry (as distinguished from actual selection of component values) of electronic counters. For such material the reader is referred to the literature.*

A brief description of a typical counter stage is given first, primarily to establish the notation and the method of attack to be used. Then design procedures are established which, if followed "cook book fashion" along with the sample calculation included, will enable the reader to select the components that should result in a satisfactory counter. For the more critical reader this is followed by a section in which the author elaborates on the method of attack set forth in the procedure. The concluding section includes a brief discussion of the characteristics which determine the suitability of various tubes for counter use.

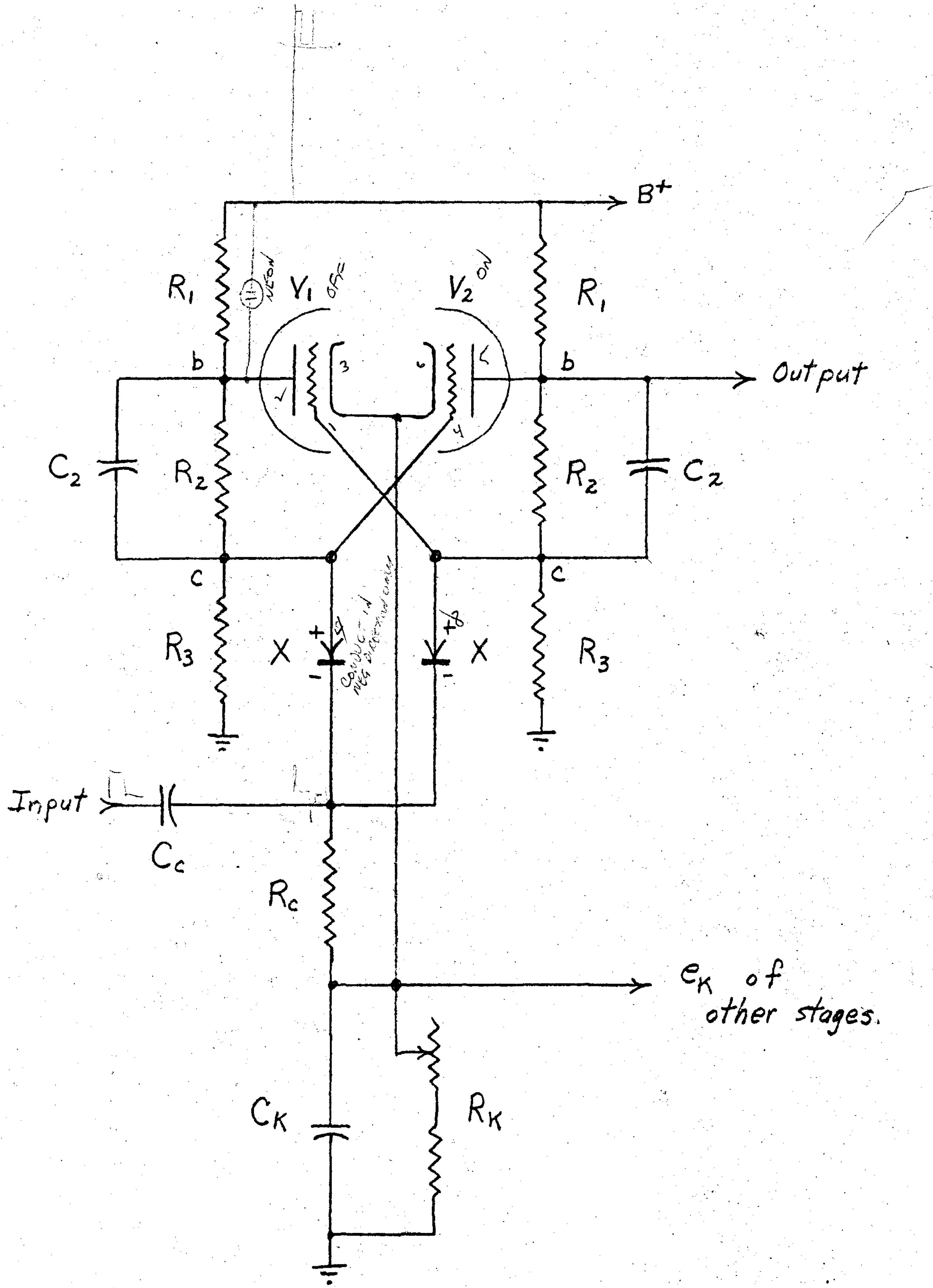
Although the method presented may not be meticulously precise, it does afford, with tools usually available to the designer, a reasonably accurate and easily worked solution. Furthermore such solutions are applicable to counters designed to operate at the higher frequencies.

* See Bibliography, especially Phelps (8) for further circuit discussions and Shea (14) for a summary of decade counters.

II. CIRCUIT CONSIDERATIONS

The basic circuit of a binary counter for which the following procedure applies is shown in Fig. 1. The Eccles-Jordan multivibrator has two stable conditions wherein one tube is fully conducting and the other is completely cut off. For the purposes of explanation assume that the left hand tube V_1 is off. The bleeder network R_1 R_2 R_3 divides down the supply voltage B^+ to a potential e_c' (where the prime is used to refer to potentials on the non-conducting side of the circuit) which is the potential on the grid of tube V_2. The bias e_k is adjusted so that V_2 operates at zero or a slightly positive bias and is definitely established as the fully conducting tube. The plate current of V_2 flowing through R_1 reduces the potential e_b and hence e_c. R_2 and R_3 must be so chosen that the resultant potential e_c is sufficiently less than e_k as to make the bias e_{gk} of V_1 greater than cut-off and thus establish it as the non-conducting tube. The coupling network C_c R_c differentiates the square wave output e_o of the previous stage. The crystal diodes are oriented so that only the negative pulses of this input reach the grids. These negative pulses are amplified and inverted by the conducting tube, coupled to the grid of the off tube, and start conduction in it. Normal multivibrator action then takes place, aided by the coupling afforded by C_2, until the circuit reaches its other stable state. Two negative pulses cause the circuit to go from one stable state to the other and back again to complete one cycle and thus yield one negative pulse at the input of the next stage. Hence each

stage divides its input by two and is therefore a binary counter.



Schematic Diagram of a Typical Counter Stage.

Fig. 1

III. PROCEDURE

1. Selection of Tube or Supply Voltage to be Used:

The following procedure provides an indication of the minimum supply voltage which can be used with a given triode, or which tubes will work satisfactorily with a given supply voltage. First assume a value of e_b equal to 60 to 70% of the supply voltage (the bias voltage decreases the effective voltage). Next draw a load line for $r_L = r_p$ from this value of e_b. As a first approximation for r_p use the value shown under "Typical Operating Conditions" or about the minimum shown on curves of r_p if available (this is around 10 K or less for most usable triodes). This load line should intersect the zero bias curve within its linear portion. If it does not, a larger supply voltage or a different tube should be used.

2. Selection of the Resistance R_1:

Normally it is desirable that r_L should be equal to or slightly greater than r_p and that r_p should be reasonably constant in the region of the operating point found in step 1 above. It must be remembered that the output frequency ($\frac{1}{2}$ the input frequency) must be below the upper half power frequency of the circuit f_2, where $f_2 = \frac{1}{\pi r_L C_T}$. As an easy approximation the total capacity C_T loading the tube is $2C_{gp} + C_{gk} + C_{pk} + C_2$ (for adequate coupling within the multivibrator C_2 should be at least equal to $2C_{gp} + C_{gk} + C_{pk}$). This then allows the designer to select r_L considering both the tube and the upper counting frequency. The selected value of R_1 normally will be the next nominal size resistor above 1.1 r_L (Thevenin's

equivalent circuit theorem will reduce this to about the previously chosen value of r_L as is shown in the sample calculations which follow).

3. Selection of the Resistance R_2:

As is shown by the curves of Fig. 3, the larger values of R_2 give the better performance and additionally are more conservative of bleeder current. The author, however, feels that 20 R_1 should be fixed as an upper limit. Again frequency response must be considered; if $R_2C_2 > T$, where T is the minimum time between input pulses, the grid of the off tube may not be near enough its stable value to permit triggering by the next pulse. This can result in division by three or more instead of by two as desired. Therefore the selected value of R_2 should be the largest available consistent with $R_2 < T/C_2$, and $R_2 < 20\ R_1$.

4. Selection of the Resistance R_3:

In order to minimize the necessity of using the trial and error technique in the actual construction of a binary counter it is necessary to run circuit analyses for all available resistors from about 0.3 to 0.8 R_2, following the form shown in the sample calculation below. The results of analyses on a 12AU7, a miniature twin triode similar in characteristics to a 6SN7-GT, are shown in Table I and plotted in Fig. 3. Those values of R_3 which yield a tube bias e_{gk} which is greater than twice cut-off will result in a satisfactory circuit. However, for optimum design, the value of R_3 which yields the maximum $e_o^2\ e_{gk}$ product is the one which makes the circuit least critical as to tolerances in components and voltages. This will be

justified in a later section.

5. Design of the Cathode Bias Network:

In laboratory models at least, it is recommended that the cathode bias e_k be made adjustable. It has also been found experimentally that operation is better when about four stages (as in a decade counter) share a common bias network than when each stage has its own individual bias circuit. Of course this requires that all stages having a common cathode bias must be designed to have identical bleeder networks, R_1 R_2 R_3, so that each stage requires the same bias. Usually a 5K potentiometer, in series with a fixed resistor if required, and both shunted by a 0.1 to 1.0 mf condenser will suffice. It will be found that the counter operates correctly at a range of values below that found for e_k in the calculations under step 4 above. The lower limit may be that point at which the circuit acts as a synchronized free-running multivibrator. Such a condition may be undesirable in certain applications. The lower limit may be found by removing the input signal and reducing the bias until the circuit just becomes free-running. It should be remembered that the cathode current of all stages flows through a common cathode bias resistance and that only one tube of each stage is conducting.

6. Selection of the Capacitor C_2 for Each Stage:

The value of C_2 is primarily determined, especially in the first stage of a counter chain where the frequency is highest, by factors set forth under procedures 2 and 3 above. C_2 must be large enough to provide proper switching action within the

multivibrator and in many cases can be made large enough (for reasonably constant frequency operation) to render each stage capable of triggering only after a time slightly less than T. This then calls for $C_2 = T/R_2$ for the first stage with C_2 being doubled in each succeeding like stage of a binary chain to prevent erratic triggering. In decade counters, where a binary chain having a natural count of 16 is forced to count 10 by the introduction of feed-back, the switching action of certain stages is no longer symmetrical, and therefore gives rise to the possibility of judicious selection of values for C_2, bearing in mind how soon the tube of such stages must be ready to be triggered. (i.e. the resistors R_2 of any stage must be equal, the condensers C_2 need not). Succeeding chains (or decades), for operation at lower frequencies, may utilize a new design of the resistance network R_1 R_2 R_3 (in order to realize the aforementioned advantages of larger resistance) giving rise to a new sequence of values for C_2. Or if the same resistance network is used, C_2 of the first stage should be about twice that of C_2 in the last stage of the previous chain. In cases where large count-downs are required C_2 eventually could become quite large in the later stages. Fortunately, however, those stages which operate at lower frequencies are inherently more stable and function adequately with reduced coupling, thereby being less sensitive to erratic triggering. Consequently an upper limit, say 200 mmf, may be placed on C_2 if proper consideration is given to the coupling.

7. Design of the Coupling Network:

The primary consideration in designing the coupling net-

work is that the time constant R_c C_c should be less than 0.2 T if possible. Since the coupling network is a load on the previous stage, it should have a high R to C ratio so as to reduce the loading effect. However C_c must be large enough compared to C_T to provide adequate coupling, but in no case should R_c be very much less than R_1 of the previous stage. When C_2 becomes considerably less than T/R_2 the coupling may be reduced proportionately. Other than these, no definite rules have been evolved experimentally.

If other types of coupling (than that shown in Fig. 1 using crystal diodes) are used, the circuit itself may place additional restrictions on the size of R_c. Cathode coupling, being a low impedance input type, will work only if R_k is comparable in value and replacable by R_c. Plate, or grid, coupling results in an additional voltage drop in R_c thereby requiring a larger minimum supply voltage.

IV. EXAMPLE OF USE OF PROCEDURE

Problem: To design a counter stage using a 12AU7 twin triode and operating at an input pulse rate of 5 Mc.

The zero bias curve for a 12AU7 is fairly straight so any reasonable supply voltage should be adequate. However a 6.25 K load line (value listed for r_p under "Characteristics") from e_b = 100 volts intersects the zero bias curve near the bottom of its most linear portion. Since this represents about 60% of the total supply voltage, B^+ is chosen as 150 volts. This satisfies step 1.

At the operating point found above $r_p \doteq 8.5$ K and $1.1\ r_p =$ 9.35 K, so use a 10K resistor for R_1. Next the upper half-power frequency is checked.

$$C_T = 2 \times 1.5 + 1.6 + 0.5 + C_2 = 5.1 + C_2 \qquad \text{so, if } C_2 = 7\mu\mu f,$$

$$\text{then } C_T = 12.1\,\mu\mu f$$

$$\text{so} \qquad f_2 = \frac{1}{\pi r_L C_T} = \frac{10^{12}}{\pi \times 10^4 \times 12.1} = 2.63 \text{ Mc.}$$

(Notice that R_1 was substituted for r_L in the above formula in order to be on the safe side.) Since f_2 is greater than the 2.5 Mc. output from the first stage step 2 is satisfied.

Since C_2 has already been selected above as 7 mmf,

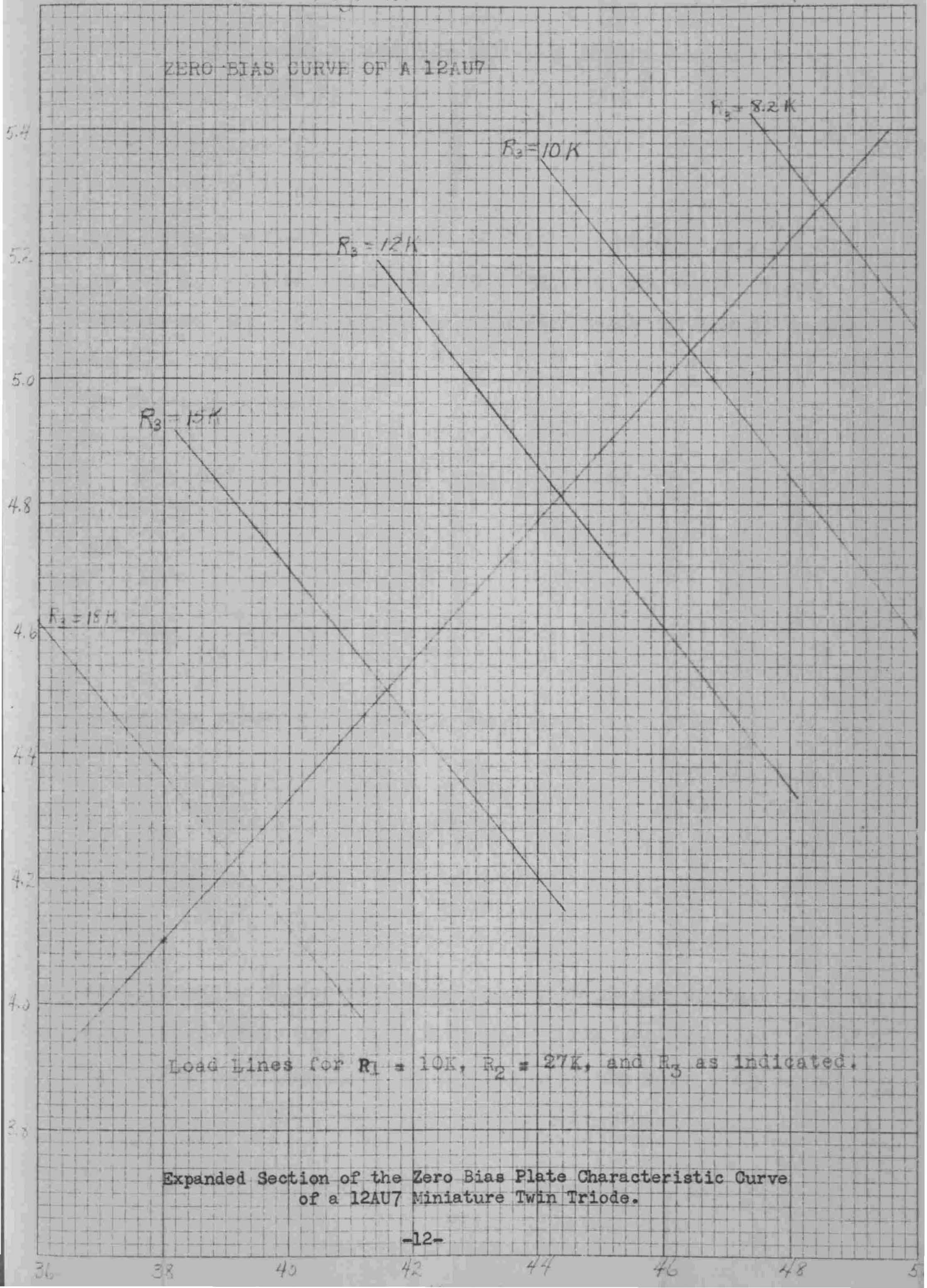
$$R_2 < T/C_2 = \frac{0.2 \times 10^{-6}}{7 \times 10^{-12}} = 28.6 \text{ K.}$$

So in accordance with step 3 select R_2 = 27 K.

Before proceeding with step 4, a section of the zero bias curve about the expected operating point is enlarged as shown

in Fig. 2. This enlargement is made so that more accurate comparative readings can be taken and thus reduce the errors in small differences taken to obtain e_{gk}.

Fig. 2.



Load Lines for $R_1 = 10K$, $R_2 = 27K$, and R_3 as indicated.

Expanded Section of the Zero Bias Plate Characteristic Curve of a 12AU7 Miniature Twin Triode.

The following values have already been selected and are included in Table I:

$$B^+ = 150 \text{ volts}, \qquad R_1 = 10\text{ K}, \quad \text{and} \quad R_2 = 27\text{ K}.$$

All nominal values of resistance (10% RMA Standards) from 0.3 to 0.8 R_2 include 8.2K, 10K, 12K, 15K, and 18K as possible values for R_3. The sample calculation which follows is based on R_3 = 10K.

By Thevenin's theorem:

$$r_L = \frac{R_1(R_2+R_3)}{R_1+R_2+R_3} = \frac{10(27+10)}{10+27+10} = 7.88\text{ K}.$$

and

$$e_b' = \frac{R_2+R_3}{R_1+R_2+R_3} \times B^+ = \frac{37}{47} \times 150 = 118.1 \text{ volts},$$

where the primes apply to the non-conducting side of the circuit.

$$e_c' = \frac{R_3}{R_1+R_2+R_3} \times B^+ = \frac{10}{47} \times 150 = 31.9 \text{ volts}.$$

$$e_{pK}' = e_b' - e_K = 118.1 - 31.9 = 86.2 \text{ volts},$$

assuming $e_k = e_c'$ for zero bias operation of the conducting tube. e_{pk} = 46.4 volts and i_b = 5.05 ma. from the intersection of the 7.88K load line from 86.2 volts with the zero bias curve.

$$e_o = e'_{pK} - e_{pK} = 86.2 - 46.4 = 39.8 \quad \text{volts.}$$

$$e_b = e_{pK} + e_K = 46.4 + 31.9 = 78.3 \quad \text{volts.}$$

$$e_c = \frac{R_3}{R_2 + R_3} \times e_b = \frac{10}{37} \times 78.3 = 21.2 \quad \text{volts.}$$

$$e_{gK} = e_c - e_K = 21.2 - 31.9 = -10.7 \quad \text{volts.}$$

$$\left| e_o^2 e_{gK} \right| = 39.8^2 \times 10.7 = 170 \times 100.$$

Table I indicates that when $R_3 = 12$ or 15K optimum results should be obtained. The plot of $e_o^2 e_{gk}$ indicates that $R_3 = 15K$ is probably the better choice.

TABLE I

TABULATION OF A SERIES OF ANALYSES TO SELECT R_3

12AU7 minature twin triode; $B^+ = 150$ volts.

R_1 in K	10	10	10	10	10
R_2 in K	27	27	27	27	27
R_3 in K	8.2	10	12	15	18
r_L in K	7.79	7.88	7.96	8.08	8.18
e_b' in volts	116.8	118.1	119.4	121.1	122.8
$e_c' = e_k$ in v.	27.2	31.9	36.7	43.2	49.1
e_{pk}' in volts	89.6	86.2	82.7	77.9	73.7
e_{pk} in volts	48.5	46.4	44.4	41.5	39.1
i_b in ma.	5.29	5.05	4.82	4.51	4.23
e_o in volts	41.1	39.8	38.3	36.4	34.6
e_b in volts	75.7	78.3	81.1	84.7	88.2
e_c in volts	17.6	21.2	25.0	30.3	35.3
$-e_{gk}$ in volts	9.6	10.7	11.7	12.9	13.8
$e_o^2 e_{gk}$ in 100's	162	170	172	171	166

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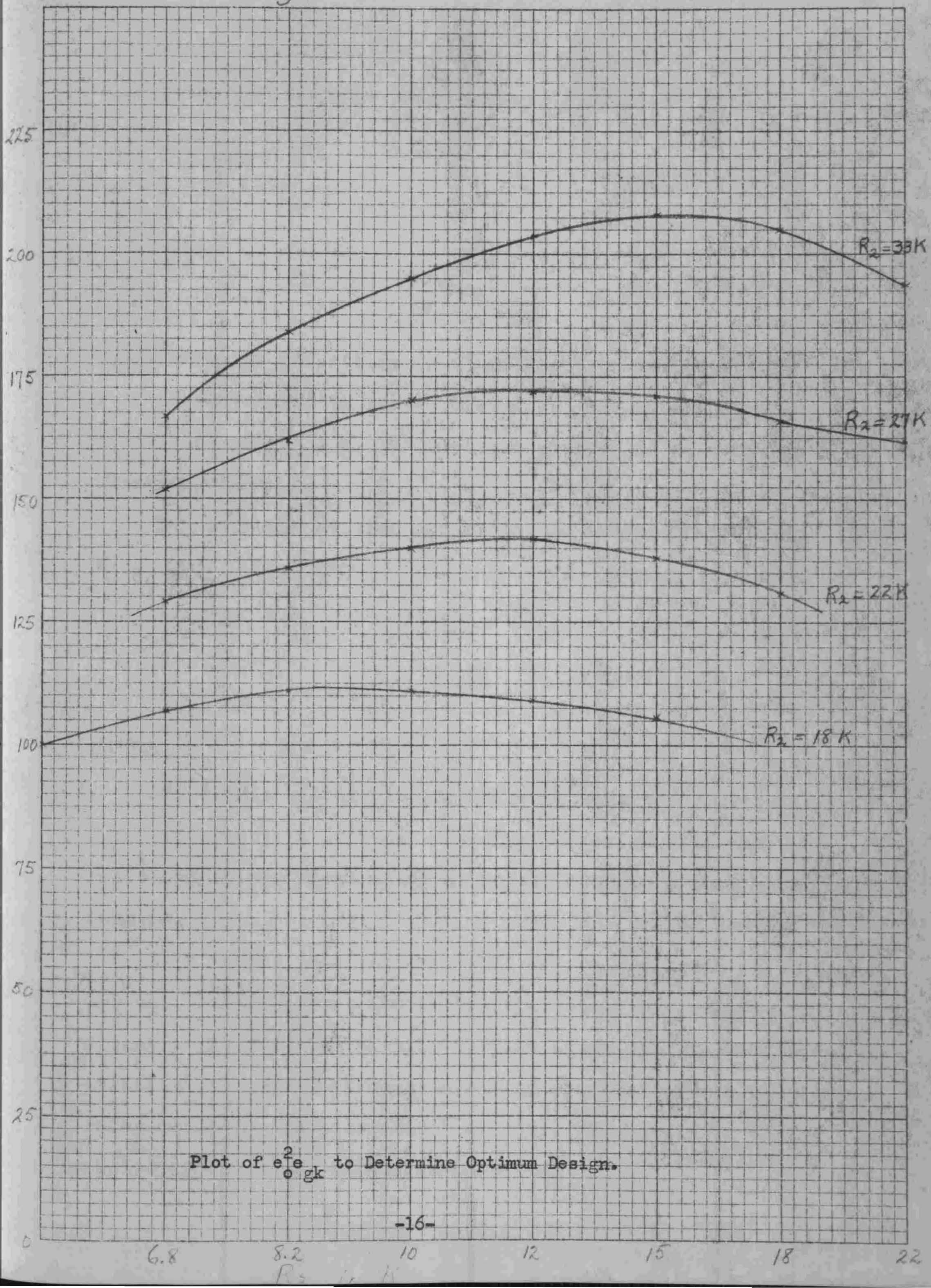
Fig. 3



Plot of $e_o^2 e_{gk}$ to Determine Optimum Design.

Assume that four like stages are to share a common cathode bias network. Then the total cathode current is

$$i_K = 4 i_b = 4 \times 4.51 \doteq 18 \text{ ma.}$$

so

$$R_K = e_K / i_K = \frac{43.2}{18} = 2.4 \text{ K.}$$

Therefore a 5K potentiometer alone would be satisfactory, or a 2K potentiometer in series with a 470 ohm resistor would be equally as good. A 0.1 µf bypass condenser is adequate at these frequencies.

For coupling between the first and second stages make $R_c = R_1 = 10K$. Then

$$C_c < \frac{0.2\,T}{R_c} = \frac{0.2 \times 0.4 \times 10^{-6}}{.01 \times 10^{6}} = 8 \mu\mu f,$$

so make $C_c = 7$ mmf.

Since this circuit is operating so near the upper half-power frequency, a 10 to 20 µh choke in series with the R_1 resistors of the first stage is recommended to afford shunt peaking.

This sample calculation should not be construed as being typical, but rather as about the upper limit of operation of a 12AU7. As such the example has the added advantage of demonstrating the amount of departure from exact adherence to the rules which can be tolerated. At lower frequencies a wider choice of component values is possible.

V. ELABORATION OF PROCEDURE

Brief explanations are given in this section to elaborate, where necessary, on certain statements made above. The following paragraphs are numbered to correspond to the steps which they explain.

1. The linear region of the zero bias curve must be used if the optimum voltage stability of the circuit is to be realized. Operation in the curved region may result in small changes of voltage or bias causing the operating conditions to shift sufficiently so that the circuit no longer functions properly.

2. The circuit is triggered by the output of the previous stage being amplified by the conducting tube. Therefore triggering is a function of both e_o and gain, but gain = $g_m R_T$ and gm is roughly proportional to i_b. The product $e_o\ i_b$ or $e_o\ g_m$ is about maximum when $r_L = r_p$. If r_L is increased slightly R_T will increase a lesser amount resulting in little loss in gain but an increase in e_o. Therefore step 2 recommends selecting R_l somewhat larger than r_p.

The upper half-power frequency of an amplifier is defined as

$$f_2 = \frac{1}{2\pi R_T C_T},$$

but since

$$r_L \doteq r_p, \quad R_T \doteq r_L/2, \qquad \text{so} \quad f_2 = \frac{1}{\pi r_L C_T}.$$

The method of establishing C_T is justified only by past performance, although it should be noted that extra weight is

given to C_{gp}.

4. The paragraph above brought out the fact that for most reliable triggering of cascaded stages both e_o and gain should be large and that gain is roughly proportional to $i_b\, r_L$. But $i_b\, r_L = e_o$ so triggering is directly related to e_o^2 for a constant R_1. For optimum voltage stability and component tolerance the bias e_{gk} should be large. Larger bias requires more trigger. Additionally the above two considerations are not mutually consistent since e_{gk} increases with increasing values of R_3 while e_o^2 decreases as may be seen by inspection of Table I. However the product $e_o^2\, e_{gk}$ does maximize as shown in Fig. 3. Intuitively it would seem that this maximum affords the best possible compromise. This has been verified experimentally for counters having the circuitry of Fig. 1.

5. Step 5 mentioned that the circuit operates correctly at a range of values below that calculated for e_k. This merely indicates that multivibrators operate best with some positive bias on the grid of the conducting tube. Of course this increases i_b and hence e_o^2 which is advantageous. This is one reason why e_{gk} should be made large; so that e_k can be decreased and still not permit conduction in the off tube. It would appear that more accurate predictions could be made by assuming operation at some positive bias, but such curves are rarely available. Therefore the procedure as set up permits a good prediction of optimum design by the use of data which is readily available.

7. The time constant of the coupling network $R_c\, C_c$ must be small enough so that it differentiates the square wave output

of the previous stage. Also C_c along with the input capacity of the stage acts as a capacity voltage divider and the voltage divides inversely as the capacity. Therefore a lower limit must be placed on C_c so that it does not take up an appreciable fraction of the input.

VI. CONCLUSIONS.

Although this article mentions the use of, and is based on triodes it should be adaptable to the design of counters using other amplifier tubes such as pentodes. (e.g. when using a pentode, in addition to screen and suppressor grid considerations, $C_T = C_{in} + C_{out}$ and $r_L \neq r_p$ but should give a load line which intersects the zero bias curve near the knee.) Also these rules are not limited to circuits like that of fig. 1, but are applicable, with minor changes, to circuits having other types of coupling and other means of utilizing the voltage supply such as a grounded cathode circuit with a negative bias supply for the grids to replace e_k.

The following comments on various twin triodes, whose characteristics have been considered by the author, are not intended to advocate any one tube as being generally best suited to counter use but rather to convey to the reader the many factors which should be considered when selecting a tube for certain expected operating conditions. The 12AU7 because of its reasonably straight zero bias curve is well adapted to use with lower supply voltages. The 12AT7 is quite similiar except that it operates satisfactorily only at higher voltages because of curvature at the bottom of its zero bias characteristic. The 12AX7 because of its high r_p (40K) can not be used at as high a frequency as the first two tubes mentioned. The 2C51 requires somewhat higher supply voltage than the 12AU7, but it does have a slightly lower r_p

and a much higher g_m. It is therefore well suited to high frequency operation. The 6J6 has published characteristics very much like the 2C51 but a great deal of variation has been found among tubes and even between the two triodes of one unit. Thus only by selection of tubes could predicted operation be obtained. Miniature tubes only have been mentioned so far because of their present popularity in counter design due to economy of space and lower capacitance. Their standard tube counterparts could be used where capacitance (and therefore frequency) or space is not a primary consideration.

Judicious use of the procedures and considerations set forth in this article should enable the designer to cope with most problems of component selection in the electronic counter field. Also, as a result of the optimum design obtained, it will be found that reasonably large variations of voltage and component characteristics can be tolerated without affecting the counting accuracy of the circuit.

BIBLIOGRAPHY

1. Blair, J. Morris. An improved current integrator. Review of Scientific Instruments. 14:64-67, March 1943.

2. Cruft Laboratory, The Electronics Training Staff of. Electronic circuits and tubes. New York, McGraw-Hill, 1947.

3. DeVault, Don. Vacuum tube scaling circuit. Review of Scientific Instruments. 12:83-85, February 1941.

4. Grosdoff, I.E. Electronic counters. RCA Review. 7:438-447, September 1946.

5. Lifschultz, H. and J.L. Lawson. A triode vacuum tube scale-of-two circuit. Review of Scientific Instruments. 9:83-89, March 1938.

6. Lifschultz, H. A complete Geiger-Müller counting system. Review of Scientific Instruments. 10:21-26, January 1939.

7. Lifschultz, H. New vacuum tube scaling circuits of arbitrary integral or fractional scaling ratio. Physical Review. 57:243-244, February 1940.

8. Phelps, B. E. Dual triode triggered circuits. Electronics. 18:110-113, July 1945.

9. Potter, John T. A four-tube counter decade. Electronics. 17:110 +, June 1944.

10. Reich, H. J. New vacuum tube counting circuits. Review of Scientific Instruments. 9:222-223, July 1938.

11. Regener, V. H. Design and use of directly coupled pentode trigger pairs. Review of Scientific Instruments. 17: 180-184, May 1946.

12. Regener, V. H. Decade counting circuits. Review of Scientific Instruments. 17:185-189, May 1946.

13. Regener, V. H. Reversible decade counting circuit. Review of Scientific Instruments. 17:375-376, October 1946.

14. Shea, H. G. Electronic true decade counters. Electronic Industries. 5:82 +, September 1946.

15. Shepherd, W. G. and R. O. Haxby. A scale of eight impulse counter. Review of Scientific Instruments. 7:425-426, November 1936.

16. Stevenson, E. C. and I. A. Getting. A vacuum tube circuit for scaling down counting rates. Review of Scientific Instruments. 8:414-416, November 1937.

17. Toomin, H. Switching action of the Eccles-Jordan trigger circuit. Review of Scientific Instruments. 10:191-192, June 1939.

18. Uspensky, J. V. and M. A. Heaslet. Elementary number theory. 13-19. New York, McGraw-Hill, 1939.

19. Wild, John J. Predetermined counters. Electronics. 20: 120-123, March 1947.

20. Wynn-Williams, C. E. The use of thyratrons for high speed automatic counting of physical phenomena. Proceedings of the Royal Society of London. A132:295-310, July 1931.

21. Wynn-Williams, C. E. A thyratron scale of two automatic counter. Proceedings of the Royal Society of London. A136:312-324, May 1932.